Passive flow control around a 2D semi-circular cylinder using porous media

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Abstract- The passive control of flow past a semi-circular cylinder is carried out. This control is achieved adding a porous layer between the solid obstacle and the incompressible fluid. A vortex-penalization method is chosen to easily tackle the modeling of the flow in the different media. Several configurations of the porous layer are investigated in order to determine the most efficient passive flow control devices.

Résumé- Contrôle passif d'écoulements autour d'un demi-cylindre. Une technique de contrôle passif utilisant une interface poreuse est mise en œuvre afin de réguler l'écoulement autour d'un demi-cylindre. La méthode vortex de pénalisation est adoptée pour la modélisation de l'écoulement dans les différents milieux. Une distribution adaptée de la perméabilité au sein de l'interface poreuse permet une réduction considérable des grandeurs physiques de l'écoulement.

Keywords : Penalization method; Vortex methods; Semi-circular cylinder; Flow control; Porous media

Mots-clés : Méthode de pénalisation; Méthodes vortex; Demi-cylindre; Contrôle d'écoulement; Milieux poreux

Version française abrégée- Le décollement de la couche limite sur une surface portante est à l'origine de la traînée aérodynamique ainsi que de phénomènes de vibration et de dissipation d'énergie. Dans l'industrie automobile ces effets sont particulièrement néfastes, provoquant une surconsommation de carburant et donc une augmentation des émissions de gaz à effet de serre. Cette étude est consacrée au contrôle d'écoulement autour d'un demi-cylindre bidimensionnel représentant une modélisation simplifiée d'un rétroviseur extérieur sur une automobile. Les rétroviseurs sont en effet responsables de 7% de la traînée totale du véhicule alors qu'ils ne représentent que 0.5% de la surface projetée. Sachant qu'un écoulement autour d'un obstacle muni d'un culot droit ne présente qu'une faible quantité de structures longitudinales tri-dimensionnelles [1, 2], une étude de contrôle en deux dimensions peut apporter des informations sur la tendance et la stratégie du contrôle préalablement à des études tri-dimensionnelles autour d'une hémisphère. De nombreuses solutions ont déjà été proposées afin de réguler l'écoulement au voisinage d'un obstacle. Parmi celles-ci on cite en premier lieu les techniques de contrôles actifs comme par exemple l'utilisation de jets synthétiques pulsés permettant le recollement de la couche limite [2]. La deuxième catégorie de dispositifs de contrôle est celle des techniques dites passives. Contrairement aux précédentes, ces dernières présentent l'avantage d'être peu couteuses et faciles à mettre en œuvre. Dans le cadre de cette étude, le dispositif de contrôle passif proposé par Bruneau et Mortazavi dans [3, 4, 5, 6] apparaît comme une solution adaptée. Il consiste à ajouter une couche poreuse entre l'obstacle et le fluide qui l'entoure. En effet, la présence d'un milieu poreux modifie les propriétés de la condition de bord à l'interface solide-fluide [7] atténuant ainsi les forces de cisaillement qui s'y exercent et donc la traînée aérodynamique. Numériquement, la résolution de ce problème faisant intervenir trois milieux différents s'effectue aisément grâce à la méthode dite de pénalisation [8]. L'approche consiste à ajouter un terme de pénalisation dans les équations gouvernant l'écoulement, ce terme étant fonction de la perméabilité du milieu. Les simulations numériques utilisent une méthode hybride particule-grille basée sur la formulation vorticité des équations [9]. Le contrôle est réalisé en ajoutant une couche poreuse sur la surface projetée du demi-cylindre et différentes répartitions de la perméabilité au sein de cette couche sont analysées, avec d'une part les couches poreuses dites homogènes présentant une perméabilité identique sur toute la couche, et d'autre part les couches poreuses dites hétérogènes dans lesquelles on distinguera deux zones de perméabilités différentes. L'efficacité de chacun de ces dispositifs de contrôle est mesurée quantitativement à l'aide de profils de pression et de vitesse, de la valeur RMS de la force de portance, de la valeur de l'enstrophie ainsi que de la force de traînée s'exerçant sur le corps, et

qualitativement grâce aux champs de vitesse et de vorticité. Les résultats montrent qu'une répartition homogène de la perméabilité au sein de la couche poreuse ne se révèle efficace que si cette perméabilité est très importante. Dans ce cas, on assiste à une très bonne régulation globale de l'écoulement avec en particulier une réduction de l'enstrophie de près de 40%. Le dispositif permettant d'obtenir les meilleurs résultats en terme de réduction de traînée est celui pour lequel la couche est divisée en deux parties où la première, correspondant à la partie frontale, est complètement solide et la seconde, correspondant aux pôles du demi-cylindre, est très perméable. Cette configuration permet en effet de réduire de près de moitié la traînée s'exerçant sur l'obstacle et assure également une importante réduction de l'enstrophie et des vibrations induites par les vortex, mesurées par la valeur RMS de la portance. Ces deux solutions étant délicates à mettre en œuvre de part la difficulté à trouver un matériau à la fois résistant et de très forte perméabilité, des configurations intermédiaires sont étudiées, donnant elles aussi des résultats satisfaisants en matière de contrôle d'écoulement.

1 Introduction

This work is devoted to the control of flow past a two-dimensional semi-circular cylinder. This obstacle can be considered as a simplified section of an outside rear-view mirror. On a ground vehicle, the mirrors, due to their spanwise position, indeed generate a non-negligible wake which interferes with the flow past car sides. They are responsible of 7% of the total vehicle drag but they only represent 0.5% of the total projected surface, which accounts for a good motivation to perform flow control past these obstacles. As it was shown in [1, 2], a flow past a square back obstacle is not dominated by longitudinal and hairpin three-dimensional vortical structures, therefore a preliminary two-dimensional study can be useful to supply information and general trends for a further control study in three dimensions around a hemisphere. The aim is to use a control device easy to set up, low cost and allowing to keep the geometry unchanged. A very suitable solution was already proposed by Bruneau and Mortazavi in [3, 4, 5, 6]. It consists in adding a porous sheath on the obstacle surface in order to reduce the vorticity generation of the boundary layer. The presence of a porous medium at the solid-fluid interface indeed imposes a kind of mixed boundary condition intermediate between the no-slip and the slip one on the solid boundary [7]. As a result, the shear forces are decreased and the flow dynamics is smoothed. Consequently, the problem we have to solve involves three different media, namely the solid obstacle, the porous layer and the fluid. An easy way to tackle it is to use the penalization method [8]. This method is based on a unique model, the Brinkman-Navier-Stokes equations, which are obtained by adding in the Navier-Stokes equations a penalization term, depending on the intrinsic permeability [3, 4, 5, 6]. Three values of this coefficient represent the three different media. This method can be easily implemented since it enables to consider the governing equations in the whole computational domain. Moreover it does not require to prescribe a boundary condition at the solid boundary or a condition at the porous-fluid interface. The penalization method has been recently implemented in vortex methods to deal with fluid-structure interaction problems[10, 11, 12]. In the present Note, we consider a two-dimensional viscous and incompressible flow past a semi-circular cylinder. The Brinkman - Vorticity Transport Equations are solved using remeshed vortex methods [9, 13, 14]. In the following we briefly describe the methodology and give the outline of the numerical simulations. Then we present the results of two-dimensional passive flow control for different configurations. A careful comparison is carried out between controlled and uncontrolled flows.

2 Methodology and numerical simulations

In this work, flow simulations are based on particle methods. The fluid particles which are displaced by convection and diffusion are characterized by their position and their vorticity. The vorticity transport is expressed by the Helmholtz equation (or Vorticity Transport Equation), obtained taking the curl of the incompressible Navier-Stokes equations and given in 2D by

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\mathbf{u} \cdot \nabla)\boldsymbol{\omega} = \frac{1}{Re}\nabla^2 \boldsymbol{\omega}, \quad \text{in } \Omega \tag{1}$$

where $\boldsymbol{\omega}$, $\mathbf{u}$ and Re respectively denote the vorticity, the velocity and the Reynolds number. The Poisson equation $\nabla^2\mathbf{u} = -\nabla \times \boldsymbol{\omega}$, obtained from continuity equation, enables to recover velocity field once the vorticity field is known.

The non-dimensional Brinkman-Vorticity Transport Equations are obtained from Eq. 1 by adding a penalization term and read

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\mathbf{u} \cdot \nabla)\boldsymbol{\omega} = \frac{1}{Re}\nabla^2\boldsymbol{\omega} + \nabla \times [\lambda(\mathbf{u}_s - \mathbf{u})] \tag{2}$$

where $\mathbf{u}_s$ represents the rigid body velocity which is zero is this work since the body is fixed and $\lambda = \mu\Phi H/\rho k\bar{\mathbf{u}}$ is the non-dimensional penalization function, in inverse proportion to the permeability of the medium (with k the intrinsic permeability, μ the viscosity, ρ the density, Φ the porosity of the porous material and H the height of the obstacle). The distinction between the three different media is thus easily performed through the value of the penalization function λ. In the fluid, the permeability coefficient is infinite, thus the fluid can be considered numerically as a porous media with a very high permeability. Thus, in the Brinkman-Vorticity Transport Equations, the penalization term vanishes and we naturally recover the Vorticity Transport Equations (Eq. 1). On the contrary, the solid has a permeability coefficient which goes to zero, it can be consequently modeled setting the penalization function to a very high value. In this study λ equals 10^8 in the solid. It was proved in [8] that solving Eq. 2 with such a value of λ was equivalent to solve Darcy's law in the solid. In conclusion, setting the λ function to a value bounded by these two extreme values would model a porous medium.

In order to analyze the effects of control we compare several global flow quantities like the drag force (F_x), computed according to the "momentum equation" given in [15], the enstrophy (Z) which measures the dissipation effects in the flow and defined by $Z = \int_\Omega |\boldsymbol{\omega}|^2 \,\mathrm{d}\mathbf{x}$ and the root mean square of the lift force ($FY\mathrm{rms}$) which evaluates the steadiness, the symmetry and the regularity of the flow and gives a relevant measure of the vortex induced vibrations (VIV) :

$$FY\mathrm{rms} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} {F_y}^2 \,\mathrm{d}t} \tag{3}$$

In the present work, a remeshed Vortex-In-Cell method [13, 9] is used. It consists in advecting particles of vorticity which are remeshed on a regular grid at every time-step. Velocity fields and diffusion are computed on the grid through FFTs and finite-difference formulas. The computational domain Ω is a $12D \times 10D$ rectangle delimited by its boundaries Γ where $D = 1$ is the diameter of the semi-circular cylinder whose back wall is centered at $(x, y) = (0, 0)$ with $-4D \leq x \leq 8D$ and $-5D \leq y \leq 5D$. The whole computational domain is meshed by an equi-spaced Cartesian orthogonal grid. As we use FFT-based evaluations to solve diffusion and Poisson equations, periodic boundary conditions are considered on the box walls Γ and a correction of velocity is performed at each time step in order to satisfy the free stream velocity $\mathbf{u}_\infty = (1, 0)$ imposed at the inlet.

3 Numerical results of the passive control

The flow control simulations are performed at non-dimensional Reynolds number Re=550. Convergence studies of the present solver for flow past a circular cylinder were carried out in [16] and shown that the grid convergence is achieved for such Reynolds number on the 2400×2000 cells grid used in this work. The time step is set to $\Delta t = 0.0025$ in order to satisfy the grid convergence. According to the parametric studies performed in [3, 4] , setting λ to 1 (high permeability) or 10 (intermediate permeability) in the porous layer shows great benefits in terms of flow regularization and drag reduction. Moreover, an efficient thickness of the layer was found to be in the range of 5% to 10% of the height of the obstacle. Here, numerical simulations are carried out setting λ to 1 or 10 in the porous sheath and fixing the thickness to $10\%D$=0.1. An accurate representation of the solution is thus ensured since the number of points inside the porous layer equals 20.

Several flow control tests are performed on a semi-circular cylinder for cases 1 to 5, depicted in Fig. 1, and compared to case 0, the uncontrolled case. Among controlled cases, we distinguish those where the porous layer is homogeneous around the body (cases 1 and 2) from those where the porous layer is split

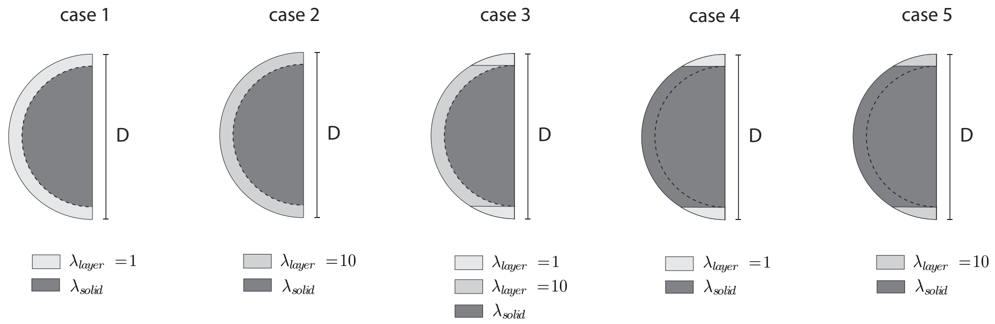

Figure 1: Cases 1 to 5 corresponding to different porous layer configurations.

	F_x	FYrms	Enstrophy
case 0 (uncontrolled case)	0.977	0.204	158.4
case 1	0.695 (-29%)	0.190 (-7%)	97.5 (-39%)
case 2	0.970 (-0.7%)	0.220 (+8%)	114.4 (-28%)
case 3	0.668 (-32%)	0.187 (-8%)	87.4 (-45%)
case 4	0.551 (-44%)	0.169 (-17%)	110.2 (-30%)
case 5	0.738 (-24%)	0.182 (-11%)	125.2 (-21%)

Table 1: Reduction effects brought by the different porous layer configurations in comparison to the uncontrolled case at Re=550.

in two regions with different permeabilities (cases 3 to 5). The asymptotic mean values of global flow quantities and the time averaged vorticity and velocity fields are respectively given for each case in Table 1, Fig. 2 and Fig. 3. Let us first compare the homogeneous cases. Certainly the case 2 is practically easier to handle and implement compared to case 1 because of its lower permeability, nevertheless the results show that it increases the VIV and does not involve drag reduction compared to uncontrolled case (Table 1). On the contrary, case 1 appears as a particularly beneficial solution inducing a drastic reduction of drag force (-29%) and enstrophy (-39%). These quantitative results are confirmed by the mean vorticity and velocity fields showing the smoothing of wake dynamics generated by the presence of the highly permeable layer. Indeed, the near wake structures are smaller and the back recirculation zone is sharply reduced (Fig. 2), implying an increase of downstream pressure (Fig. 5) and thus a reduction of drag forces. Finally, the vortices swirl with lower velocity (Fig. 3 and 4). Concerning heterogeneous devices, case 3 shows benefits which are very comparable to those of case 1. We note that the only difference with case 2 is the presence of high permeable poles in the layer. The latter allow an eddy detachment from the wall (Fig. 2) and a drastic increase of downstream pressure (Fig. 5). The case 3 thus enables to significantly regularize the flow using highly permeable material introduced in both edges of the body. Nevertheless, the mix of high and intermediate permeabilities induces difficulties to industrially build such a layer. The case 4 overcomes this problem since the front part of the layer is no more permeable, but completely solid. Compared to case 3, the reduction of enstrophy is less important, but the one of drag force (-44%) and FYrms (-17%) are considerable. The pressure profiles (Fig. 5) as well as velocity field and profiles (Fig. 3 and Fig. 4) confirm these results, showing a significant reduction of the mean velocity of the flow particles. We also notice the decrease of the transversal dimension of the wake and of the vorticity values at the back of the obstacle (Fig. 2). Unquestionably, case 4 is the best device in terms of drag and VIV reduction. The fifth and last test case, made of intermediate permeabilities on both edges of the body, corresponds to a more realistic device. The benefits given by such a device are surprisingly far better than the one obtained with the homogeneous case 2 or the uncontrolled case, which emphasizes the importance of the positions of the permeable zones. These results make case 5 a suitable and affordable device for flow control.

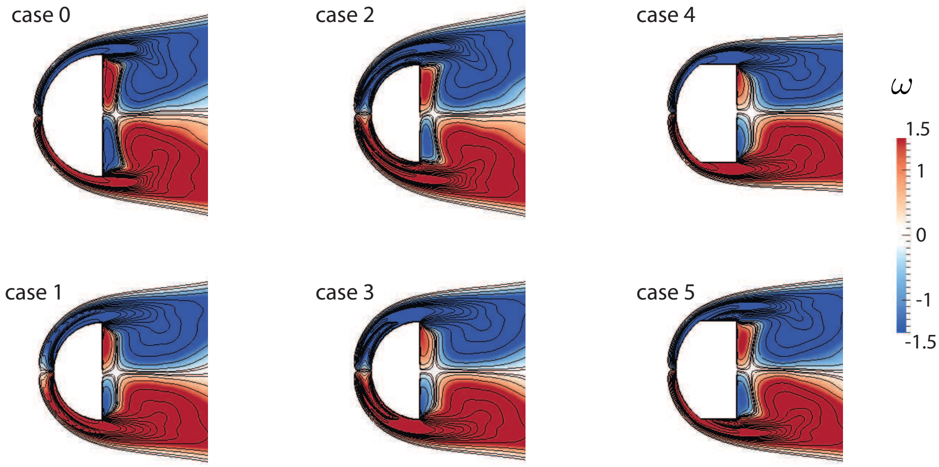

Figure 2: Zoom of the time averaged vorticity fields and isolines for the flow past a semi-circular cylinder at Re=550.

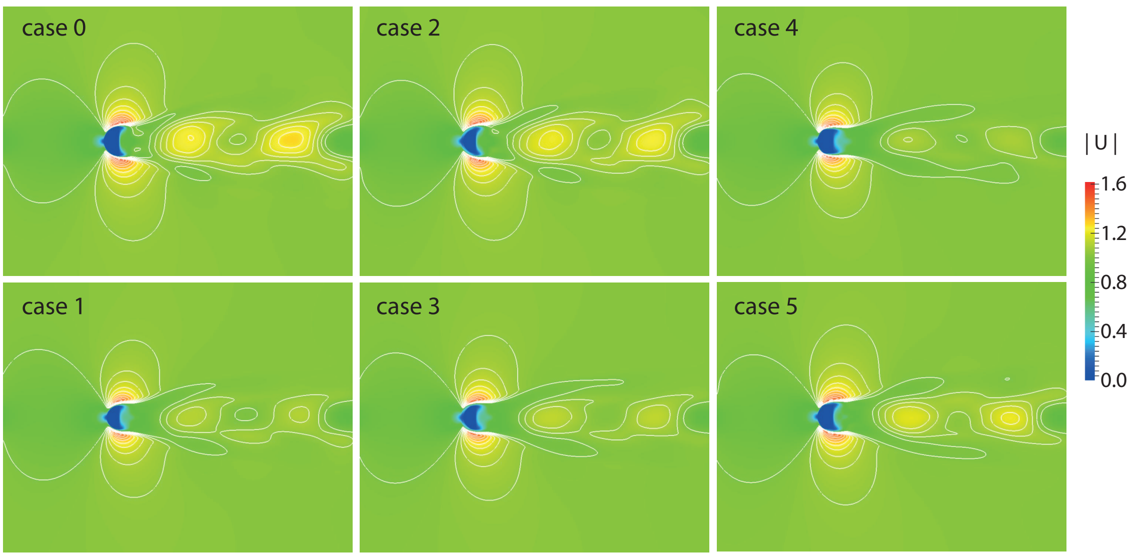

Figure 3: Fields and isolines of time averaged velocity magnitude for the flow past a semi-circular cylinder at Re=550.

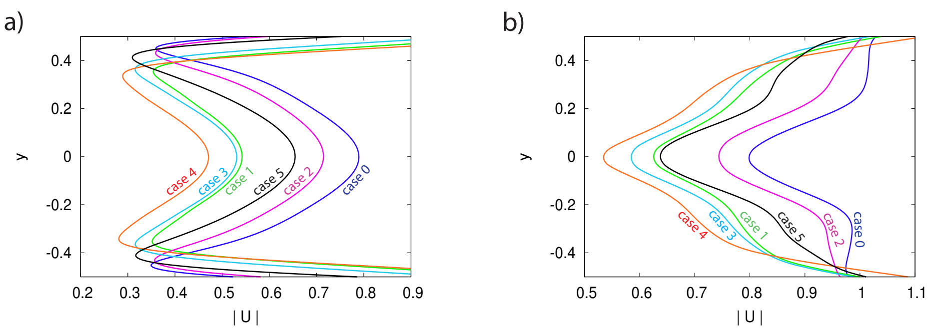

Figure 4: Profiles of time averaged velocity magnitude at a) $x = 0.2$ and b) $x = 0.5$

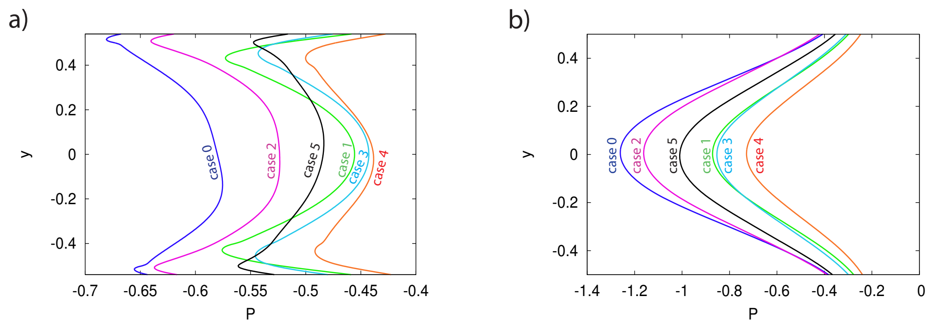

Figure 5: Profiles of time averaged pressure at a) the rear end of the body and b) $x = 0.5$

4 Conclusion

Passive control devices are handled over a two-dimensional semi-circular cylinder using porous interfaces in order to reduce the aerodynamic drag, the dissipation effects in the fluid and the vortex induced vibrations. The best drag reduction is obtained using porous interfaces with high permeabilities on lower and upper edges of the body. The same configuration with intermediate permeability at the poles can be considered as a good compromise between manufacturing constraints and control efficiency. Further studies will entail a passive control for high Reynolds flows (closer to real problems) and 3D cases.

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